Nuclear Quadrupole Resonance

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LONG-TERM GOALS

Joint Service Explosive Ordnance Disposal (JSEOD) Notional Concept #99-001, Non-Intrusive Filler Detector (NIFD) calls for a device that will allow an EOD Technician to determine the internal contents of Unexploded Ordnance (UXO) and Improvised Explosive Devices (IED). The system would be hand held, easily operated by one or two persons and relatively inexpensive. The system would inspect a UXO or IED from an inspection standoff of 1-2 inches and provide reliable indication of the make up of the explosive, inert, chemical, biological or other filler. PEO-MIUW/PMS-EOD is currently beginning an Analysis of Alternatives (AOA) to field an NIFD in FY03. This effort focuses on reducing the risk of fielding a NIFD based on neutron interrogation by developing new collimated detectors and signal processing techniques to reduce interrogation time.

OBJECTIVES

In FY00, the NAVEODTECHDIV began exploring the use of Nuclear Quadruple Resonance (NQR) for detecting IEDs. Since the majority of IEDs of interest were encased in non-metallic containers, the inability of NQR to penetrate and receive signals through metal was not considered a detriment. The focus of this task shifted in the 3rd quarter of FY00 based on a decision by the JSEOD Notional Concept Working Group to accelerate the fielding of a NIFD. A joint Broad Agency Announcement that included identification technologies had just closed with the submission of NQR, neutron interrogation, and trace chemical detection proposals. Since the NIFD must identify both IEDs and UXO, the NAVEODTECHDIV decided to select a joint proposal by the University of Western Kentucky and SAIC for methods for reducing interrogation time of an existing neutron interrogation technology.

The original focus on NQR was based on the ability to detect many explosive compounds including the low vapor pressure compounds that are hard to detect by vapor/trace detection. Shortfalls found with NQR included the fact that it does not detect liquid explosives, explosives without QR-active nuclei, and amorphous explosives. Research showed that the explosives not detectable by NQR are detectable with Nuclear Magnetic Resonance (NMR). Discussions were held with Quantum Magnetics Inc. about their LiquiScan NMR technology. This technology was developed to detect common flammables and liquid explosives for airport security. The research in FY00 focused on determining the suitability of combining the NQR and NMR technologies together in one single sided system to produce a highly reliable detection system.

APPROACH

The NMR technique is based on the ability to measure the characteristic absorption of radio frequency (RF) signals by a target material. To induce nuclear magnetic resonance, a sample material is placed in a volume surrounded by large magnets that produce a magnetic field. The nuclei of the sample material, subjected to this directional magnetic field, align themselves according to their nuclear magnetic moment. As sample atoms are energized by an external source, they will transition between discrete energy states, as directed by their magnetic alignment. The measurement and chemical interpretation of these energy transitions constitute NMR analysis.

NMR techniques can determine the presence of materials with the signature chemical composition of explosives. All samples, however, must be passed through the magnetic coils, thus limiting accessibility and configuration of NMR systems.

Nuclear Quadrupole Resonance, a derivative of NMR, is a bulk inspection technology for detecting crystalline explosive solids containing nitrogen 14 (N^{14}) nuclei (hexogen (RDX), TNT, and nitrates). Unlike NMR where an external magnetic field is needed, quadrupole resonance takes advantage of the material's natural crystalline electric field gradient (produced by the electric forces that hold the atoms of a molecule together) which aligns the electric quadrupole moments of the nuclei. As a result, the material being diagnosed need not be contained within large magnetic field-producing coils.

When a low-intensity RF signal is applied to the material at certain frequencies, the alignment of the nuclei is altered. As the RF is removed, the nuclei precess to their original state, producing a characteristic radio signal. The signal can be measured for analysis. In a method similar to tuning a radio to a particular station, NQR can be used to detect explosives by tuning a device to scan for frequencies specific to different explosives.

The uniqueness of a molecule's field allows NQR technology to be highly compound specific. For explosives, NQR signals of the N^{14} nuclei range from several hundred kilohertz to a few megahertz. NQR has been demonstrated to detect RDX, TNT, PETN and explosives containing the chlorine nuclei. It is suggested that initially a (one sided) NQR detection device that is portable, extremely selective and accurate for solid crystalline explosive, be designed.

With the NQR technique, one can detect many important explosives, including low vapor pressure compounds. NQR detection sensitivity for RDX and TNT commonly found in landmines is sufficient to standardize a go-no go detection device. Plastic explosives are detectable because the explosives are crystalline and are embedded in plastic. Elements without active nuclei such as nitrogen, chlorine, aluminum, liquid explosives, and amorphous explosive are not detectable by quantum resonance. NMR can detect these types of materials.

After the decision to accelerate the NIFD program was made, focus switched to the Pulsed ELemental Analysis with Neutrons (PELAN) device. PELAN utilizes a pulsing deuterium-tritium (d-T) neutron generator. The generator provides 14 MeV neutrons to initiate various nuclear reactions with the target. Gamma ray returns from the neutron-target interaction are analyzed to determine the target filler material.

WORK COMPLETED

NQR is an analytical chemistry technique that was adapted for the rapid detection of explosive material by Dr. A. Garroway at the Naval Research Laboratory. The NAVEODTECHDIV consulted with Dr. Garroway on the feasibility of utilizing a combined NQR/NMR technique. Dr. Garroway questioned the ability to extend NMR to a hand held device but, suggested working with Quantum Magnetics Inc. on determining the feasibilty of this approach. Quantum Magnetics was currently finishing a $13,000K program for the Defense Advanced Research Project Agency (DARPA) for a man portable mine detection system and had worked with Dr. Garroway in the past in fielding NQR prototypes for the Federal Aviation Agency (FAA).

Dr. Garroway also agreed that NQR alone may be applied to a field fabricated detection system for large vehicle bombs. Since the response of an NQR device is related to the 3rd power of the mass of the explosive, a circular wound antenna around the exterior of a truck was envisioned as a means to quickly determine the presence of explosive in a truck sized IED.

Research began on NQR/NMR to develop an approach for developing a hand held detector and determine the possibility of testing a field-fabricated system. This research was in conjunction with on-going defense efforts at Penn State University and Michigan Tech in the area of using NQR to detect explosive materials.

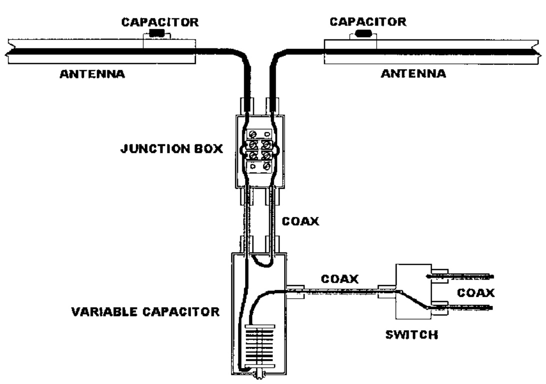
Discussions were held with Professor Jeffrey L. Schiano, Professor of Electrical Engineering at Penn State and Mr. Mark D. Ginsberg, Principal Investigator for the Engineer R&D Center of the US Army Corps of Engineers. Their system has some advantages such as automatic adjustments of pulse parameters to increase probability of correct detection and to decrease false alarm rate. They have the capability for self-diagnostics, to inform the user of the size of the search region. Penn State was confident that they could create a hand-held NQR detector due to their continuing advancements.

Professor Schiano believes that his research has advantages over other efforts in the NQR field due to the use of a High Temperature Superconducting (HTS) coil. Inadequate signal to noise ratio is a major concern with the detection of TNT and results in a time consuming process. To lower the detection time, they propose to increase the SNR by replacing a copper search coil with a HTS resonator. This will increase the quality factor, Q, of the circuit during the receive mode. As the SNR is proportional to the square root of Q, it may be possible to significantly improve the receiver sensitivity by employing HTS detection coils. One potential disadvantage with this type of system is that a high Q can cause substantial non-linearity in receiver performance, mandating careful calibrations in routine use. Penn State has fabricated two HTS resonators. The shortfall of the HTS resonator for a hand held application is the need for a liquid nitrogen tank to cool the coil to 77^{o}K. He discussed an idea to use a container the size of the thermos to include the HTS resonator and a liquid nitrogen tank, which could conceivably last for 1 hour before refill.

Discussions were held with Quantum Magnetics to understand research that has been completed by other programs (DARPA, FAA. etc.) and to understand the capabilities and limitations of their system when used for IED detection. From these discussions, it is apparent that the existing system needs to be tested further to include additional explosives in the identification database. With DARPA funding, Quantum Magnetics has concentrated on NQR detection of RDX and TNT, two common explosives found in landmines. With FAA support, they have focussed their efforts on identification of PETN, ammonium nitrate, and black powder. Quantum Magnetics has not yet determined the detection sensitivity for HMX, tetryl, ammonium perchlorate, sodium nitrate, sodium perchlorate, and urea nitrate, although literature data suggests that there are no significant barriers to detecting these compounds. Since there are a large number of explosives available to IED fabricators, a reliable detector must have the capability to detect all explosive materials. The limitations of NQR interrogation of metallic encased items were also addressed. Metal casings prevent the NQR pulse from interacting with the explosive. As a result, there is no opportunity for explosive detection and identification. However, metallic items have a detecting frequency to notify the user that an interference has occurred and that a “no detection” indication could be a false negative. Quantum Magnetics has structured common frequencies that will be detected when a metallic item might be encompassing explosive materials. Since IED’s are generally not encased in metallic cases, this limitation did not pose a problem initially. Data from recent field tests from the DARPA mine detection and from this project show that NQR can be provided in a man-portable, if not hand held configuration. The system Quantum Magnetics proposed was a multi-sensor technique with NQR and NMR. The explosives that are not detectable with NQR are detectable with NMR, such as liquid explosives and common flammables. This combined system would produce a highly reliable go, no-go gauge, in which a no-alarm response indicates the absence of a threat with a high degree of confidence. However, the NMR system will not penetrate thick metallic cases without a very large magnetic field.

Dr. Mike Shamaiengar visited Michigan Tech University to acquire a better understanding of NQR from Professor B. Suits. The visit consisted of discussions concerning calculations of nuclei spin, effects of static magnetic fields, effects of pulsed RF fields, and some operator methods for use of NQR. This visit was conducted to enhance Dr. Shamaiengar’s knowledge and ability to calculate other EOD uses for NQR technology. An antenna design for a hand held device was researched and the necessary design parameters were calculated. The antenna was fabricated to apply the knowledge that was acquired from the visit to Michigan Tech.

A.



B.

Figure 1.

A. Schematic of the Antenna for NQR Detection

B. Antenna designed by Dr. Shamaiengar.

To apply the knowledge and understanding of the concept and calculations, an in-house plan was devised to use the NQR technique for detecting explosive material in a large IED. A Ryder truck filled with ammonium nitrate was selected for the sample calculation. A circular loop centered in the x,y plane around the z-axis was used to theoretically model the measurement of the magnetic field along the z-axis. For this example, we wish to calculate the power needed to emit the necessary transmit pulse. We start with:

$$B_z(z) = \frac{\frac{1}{2}\mu a^2}{(a^2 + z^2)^{\frac{3}{2}}} I$$

where

μ =	$4\cdot\pi\cdot(10^{-3})$	(Gauss·m /amp)
I =	coil current	(amps)
B =	field strength	(Gauss)
a =	radius of coil	(m)

A 5 Gauss field is required at the center of the explosive. The longest dimension of the truck is 24 feet, so the radius of the coil, a, is 12 ft (3.658 m). A typical impedance value for the coil is 50Ω. Assuming the explosive material is 3 ft (0.9144m = z) above the coil and solving the above equation for I, the required current is 3190 amps. Using a properly tuned coil and a typical Q value for a transmit circuit (~10), the required power is

$$P = (\frac{I}{Q})^2 R = (320\ amps)^2\ (50\Omega) \cong 5MW$$

The calculated power requirement greatly exceeds the power generation capability of equipment generally accessible to an EOD technician in the field.

RESULTS

The research into NQR showed that while promising for non-metallic and thin metallic walled IEDs and UXO, the emerging EOD requirement for thick cased UXO filler identification could not be met. The calculations on a field fabricated large IED detection system showed that while feasible, the system would require a large power source not readily available to EOD field units. The selection of the PELAN technology and the risk reduction efforts associated with the planned 6.2 effort for the 4th quarter FY00 and FY01 better support the EOD needs.

IMPACT/APPLICATIONS

The study of NQR/NMR technologies will be transitioned to the JSEOD AOA for a NIFD. The information gathered in FY00 has helped to guide the pre-AOA process and the development of a JSEOD Notional Concept Paper. The risk reduction efforts planned in the PELAN effort directly support the reported shortfalls of fielded neutron interrogation systems.

TRANSITIONS

PEO-MIUW, PMS-EOD will start an AOA in FY01 for the fielding of a NIFD. The work on NQR/NMR has transitioned to the pre-AOA paper and the PELAN work will provide a risk reduction for fielding an neutron interrogation system in FY02.

RELATED PROJECTS

Quantum Magnetics is funded by the FAA to develop a NQR system for detection of explosives in luggage. The FAA has also funded the LiquiScan NMR technology for detection of potential hazardous liquids.

Quantum Magnetics is funded by DARPA to use NQR for mine detection.

REFERENCES

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